



# Search for new resonances decaying into W, Z and H bosons at CMS

DIS 2017  
BIRMINGHAM

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on behalf of the CMS collaboration

April 5, 2017

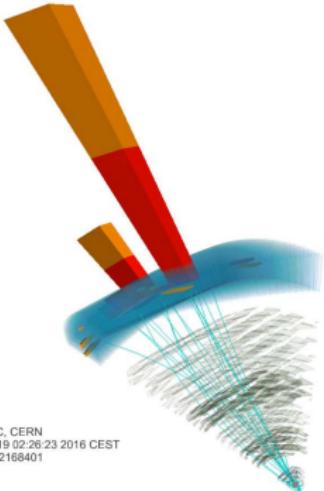


**Universität  
Zürich<sup>UZH</sup>**

# Introduction

- Heavy BSM resonances ( $\gtrsim 1$  TeV) may decay into SM bosons (**W, Z, H**)
- Plethora of final states, each one with its own peculiarities:

	$V \rightarrow q\bar{q}$	$W \rightarrow \ell\nu$	$Z \rightarrow \ell\ell$	$Z \rightarrow \nu\nu$	$H \rightarrow b\bar{b}$
$V \rightarrow q\bar{q}$	<b>VV <math>\rightarrow q\bar{q}q\bar{q}</math></b>	<b>WV <math>\rightarrow \ell\nu q\bar{q}</math></b>	<b>ZV <math>\rightarrow \ell\ell q\bar{q}</math></b>		<b>VH <math>\rightarrow q\bar{q}b\bar{b}</math></b>
$W \rightarrow \ell\nu$	<b>WV <math>\rightarrow \ell\nu q\bar{q}</math></b>				<b>WH <math>\rightarrow \ell\nu b\bar{b}</math></b>
$Z \rightarrow \ell\ell$		<b>ZV <math>\rightarrow \ell\ell q\bar{q}</math></b>			<b>ZH <math>\rightarrow \ell\ell b\bar{b}</math></b>
$Z \rightarrow \nu\nu$				<b>ZH <math>\rightarrow \nu\nu b\bar{b}</math></b>	<b>ZH <math>\rightarrow \nu\nu b\bar{b}</math></b>
$H \rightarrow b\bar{b}$	<b>VH <math>\rightarrow q\bar{q}b\bar{b}</math></b>	<b>WH <math>\rightarrow \ell\nu b\bar{b}</math></b>	<b>ZH <math>\rightarrow \ell\ell b\bar{b}</math></b>	<b>ZH <math>\rightarrow \nu\nu b\bar{b}</math></b>	<b>HH <math>\rightarrow 4b</math></b>



CMS Experiment at LHC, CERN  
Data recorded: Fri Aug 19 02:26:23 2016 CEST  
Run/Event: 279024 / 602168401  
Lumi section: 378

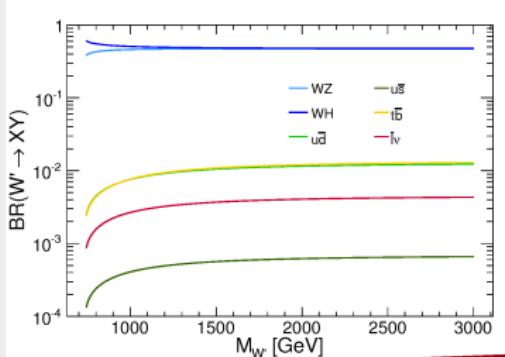
## Experimental challenges

- SM bosons decay mostly to quarks ( $q\bar{q}, b\bar{b}$ )
- Due to the large Lorentz boost  $W, Z, H$  decay products merge into a single jet
- Clustered within a large-cone jet ( $R = 0.8$ )
- Investigation of the **jet substructure**
- **Groomed jet mass** to mitigate pileup contamination

# Theoretical motivations

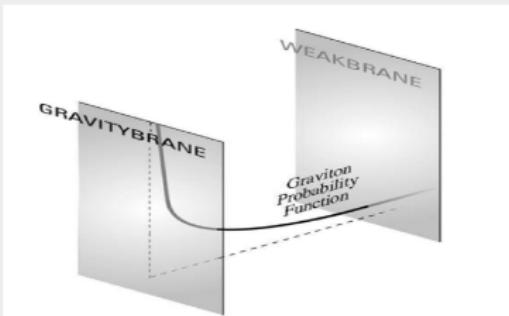
## Heavy Vector Triplet (HVT)

- Heavy  $Z'$ ,  $W'$  predicted by several models: Little Higgs, composite Higgs, Minimal Walking Technicolor
- Described by a simplified Lagrangian in the HVT framework [1] [2]
- 3 new BSM vector fields  $V^+$ ,  $V^-$ ,  $V^0$
- Two possible scenarios:
  - couplings to fermions dominating (**Model A**)
  - coupling to fermions suppressed w.r.t. to SM bosons (**Model B**):



## Warped Extra Dimension (WED)

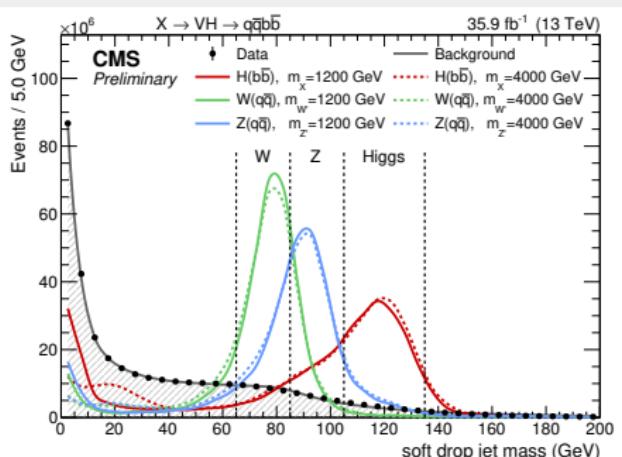
- WED models as possible solution to the hierarchy problem



- Radion (spin-0) and Graviton (spin-2)
- Radion scale  $\Lambda_R$  depends on Planck scale, Warp factor  $k/\bar{M}_{Pl} \sim \text{TeV}$
- May have similar coupling strength to SM fermions and gauge boson
- Production through DY and gluon-fusion, decay to WW, ZZ, HH

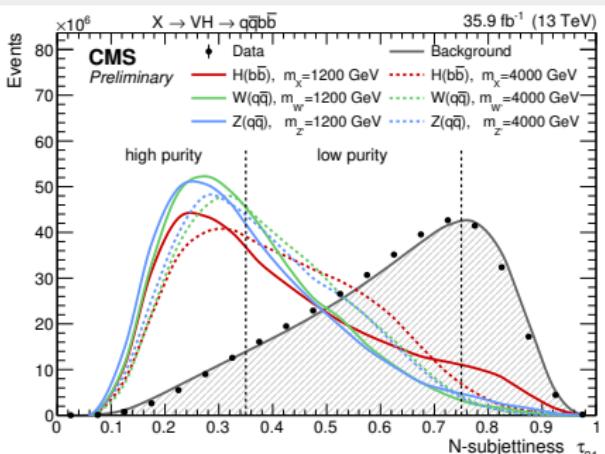
## Grooming and jet mass

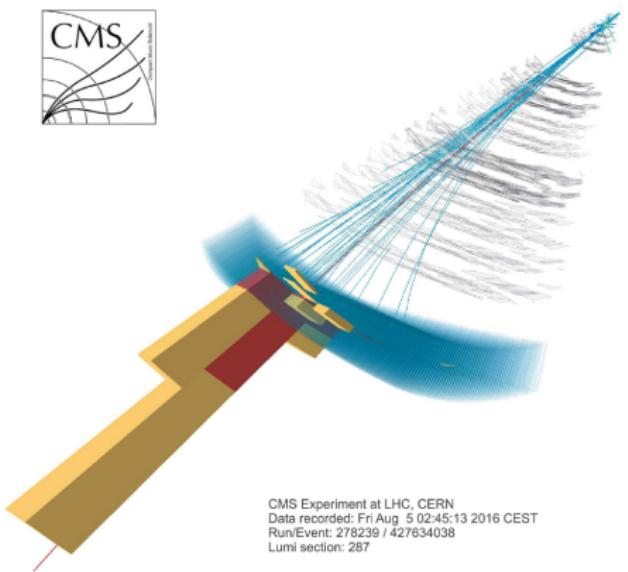
- **Pruning [1]** (legacy 2015)
- **Soft drop [2] + PUPPI [3]** (2016)
  - stable vs pileup
  - good  $m_j$  resolution (10%)
- Orthogonal  $m_j$  categories:
  - W**  $65 < m_j < 85$  GeV
  - Z**  $85 < m_j < 105$  GeV
  - Higgs**  $105 < m_j < 135$  GeV



## Vector boson tagging ( $V \rightarrow q\bar{q}$ )

- CMS uses **N-subjettiness** ( $\tau_{21}$ ) +
 **PUPPI** [4]
  - measures how consistent is the jet with the 2 sub-jets hypothesis
- Scale factor and uncertainties derived from  $W \rightarrow q\bar{q}$  in  $t\bar{t}$ -enriched sample
- Categorization according to purity:
  - **High Purity (HP)**  $\tau_{21} < 0.35$
  - **Low Purity (LP)**  $0.35 < \tau_{21} < 0.75$

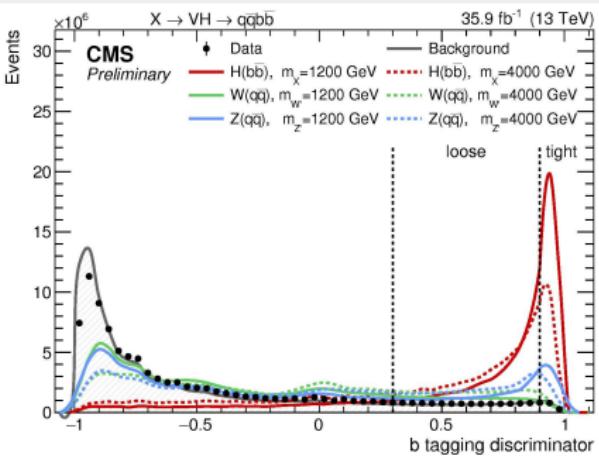




## Higgs boson tagging ( $H \rightarrow b\bar{b}$ )

### ■ Double-b tagger algorithm [5]

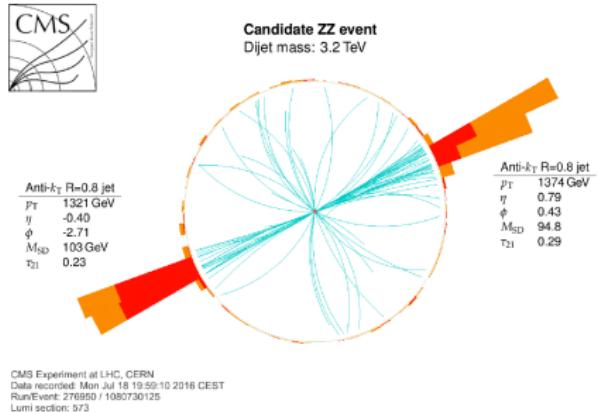
- exploit b-tagging to identify **two** b-quarks within the same jet
- also uses soft lepton ( $e, \mu$ ) information
- combines tracking and vertexing information in an MVA



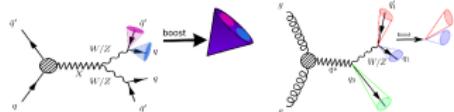
$X \rightarrow VV \rightarrow q\bar{q}q\bar{q}$

CMS-PAS-B2G-17-001

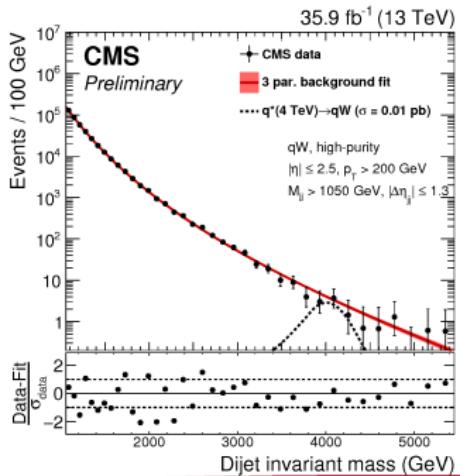
- All-hadronic resonance search with double (VV) or single (qV) V-tag



- At least 2 AK8 jets with  $p_T > 200$  GeV,  $|\eta| < 2.5$
- Back-to-back topology:  $|\Delta\eta| < 1.3$
- Categorization in 6 (VV) + 4 (Vq) signal regions:
  - jet(s) mass: WW, WZ, ZZ
  - $\tau_{21}$ : HP HP, HP LP

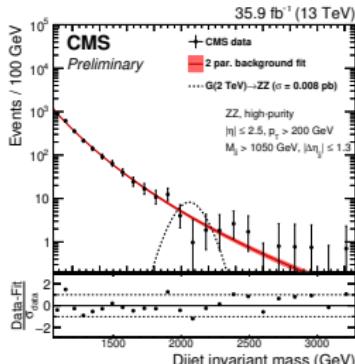
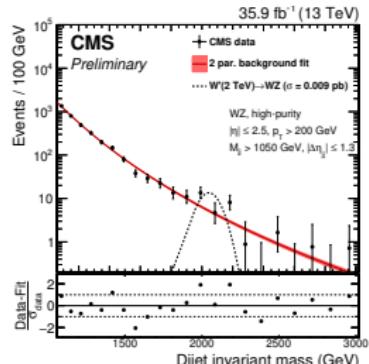
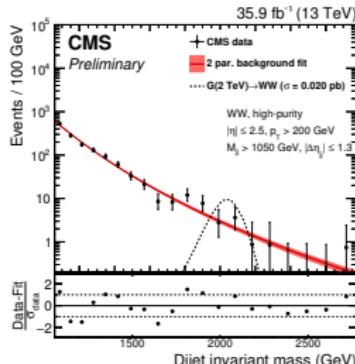


- Background estimation:  
“bump-hunt” fit with power law functions directly to data
- Number of parameters (2-5) determined with F-test

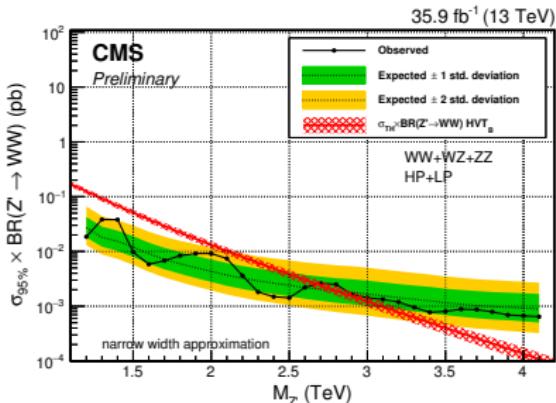
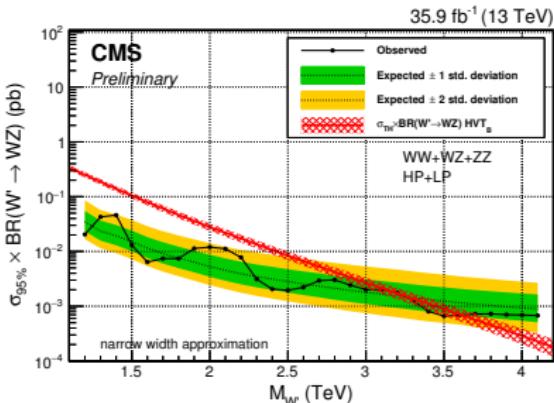


$X \rightarrow VV \rightarrow q\bar{q}q\bar{q}$ 

CMS-PAS-B2G-17-001



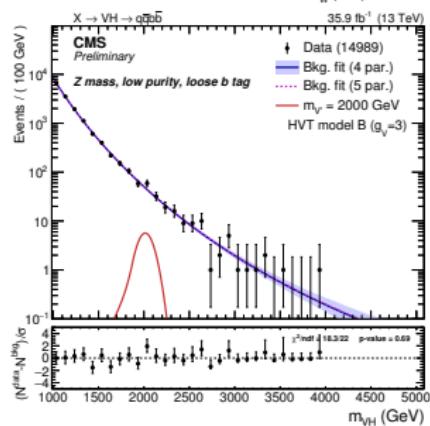
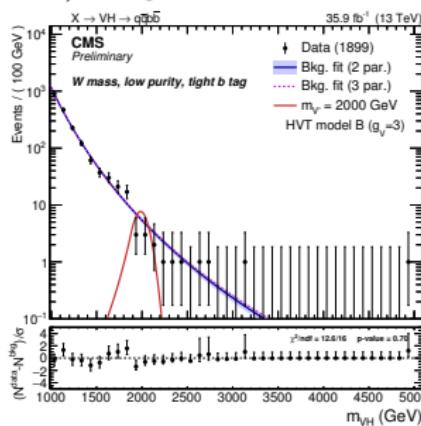
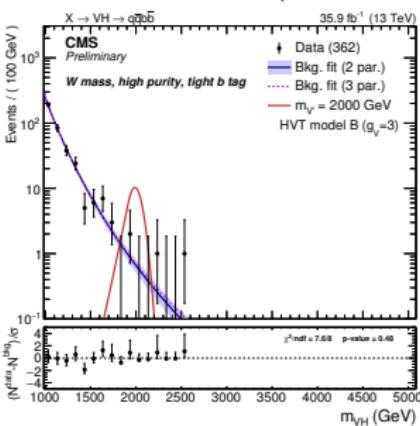
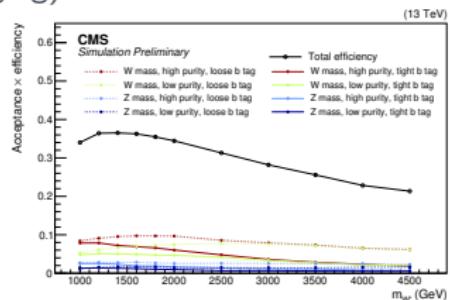
- No significant excess found in data
- Currently, the most stringent limits on  $m_{Z'} < 2.7 \text{ TeV}$  and  $m_{W'} < 3.6 \text{ TeV}$



$X \rightarrow VH \rightarrow q\bar{q}b\bar{b}$

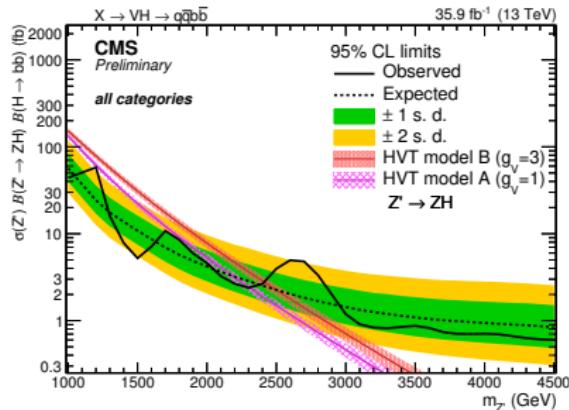
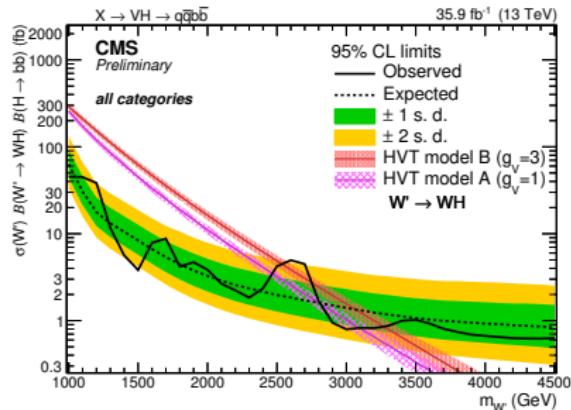
CMS-PAS-B2G-17-002

- All-hadronic search for  $V \rightarrow q\bar{q}$  and  $H \rightarrow b\bar{b}$  resonances
- Similar topology and background estimation to VV resonances search, but dedicated identification for  $H \rightarrow b\bar{b}$  (b-tagging)
- Same preselections as VV,  $2 \times 2 \times 2 = 8$  categories depending on:
  - 1 **V jet mass:** W ( $65 < m_j < 85$  GeV) or Z ( $85 < m_j < 105$  GeV)
  - 2 **V jet  $\tau_{21}$ :** high purity ( $\tau_{21} < 0.35$ ), low purity ( $0.35 < \tau_{21} < 0.75$ )
  - 3 **H jet b-tagging:** tight ( $Hbb > 0.9$ ) and loose ( $0.3 < Hbb < 0.9$ ) b-tag

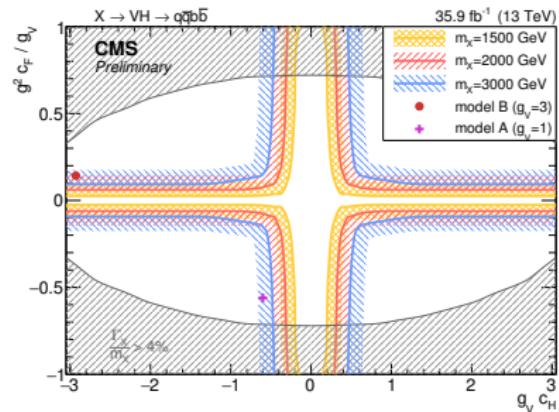


$X \rightarrow VH \rightarrow q\bar{q}bb$ 

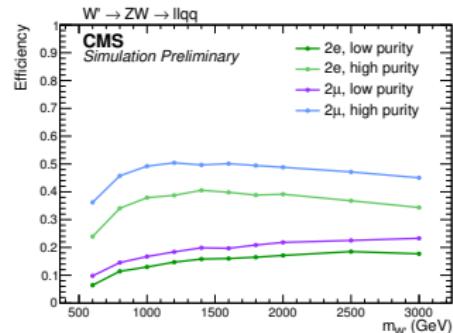
CMS-PAS-B2G-17-002



- No significant excess found in data
- Sensitivity close to VV search ( $m_{Z'} < 2.4$  TeV,  $m_{W'} < 3.3$  TeV)
- Combined exclusion in triplet hypothesis ( $m_{V'} < 3.4$  TeV)
- Interpretation in model A and B, also in the HVT parameter space
- ATLAS  $3.3\sigma$  excess at  $m_X \sim 3$  TeV not confirmed

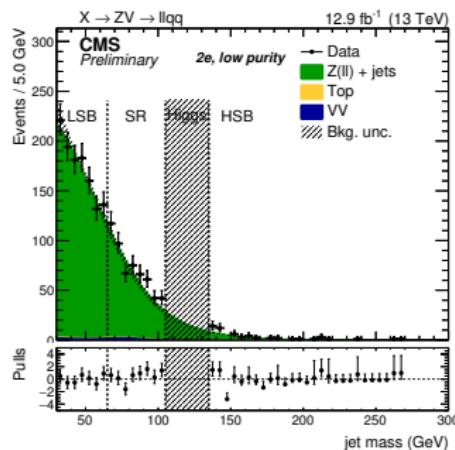
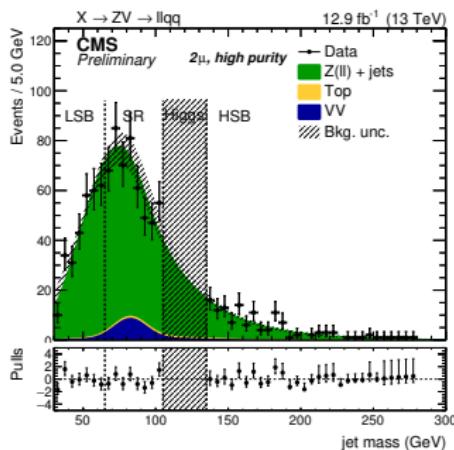


- Search for resonances in the  $Z \rightarrow ee$  or  $\mu\mu$ ,  $V \rightarrow q\bar{q}$  (either W or Z) channel
  - clean final state (leptons)
  - good mass resolution
  - large signal efficiency ( $\sim 65\%$ )
  - penalized by  $Z \rightarrow \ell\ell$  branching fraction
- Search with ICHEP dataset ( $12.9 \text{ fb}^{-1}$ )
- Usual  $\tau_{21}$  categorization (HP, LP)



- $\alpha$ -method background prediction  
[normalization]:

- 1 Use suitable functions to parametrize main bkg (Z+jets)
- 2 Fit them to data in the  $m_j$  sidebands (LSB, HSB)
- 3 Take shape of secondary bkg (VV,  $t\bar{t}$ ) from simulation



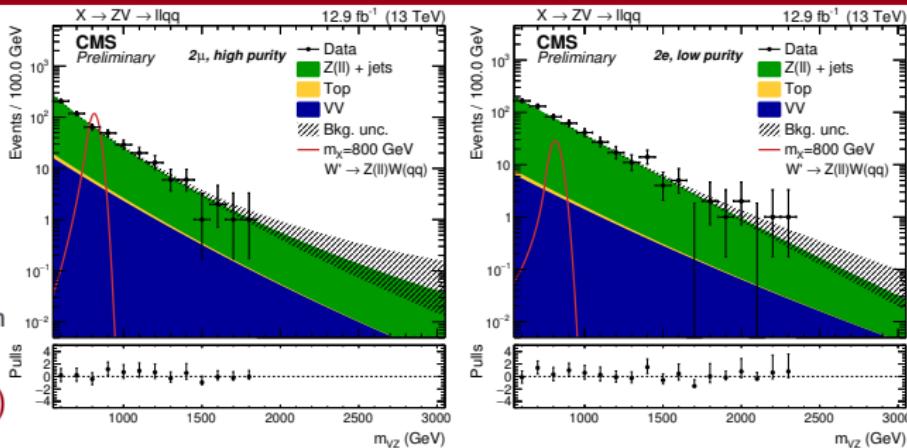
- $\alpha$ -method background prediction [shape]:

- 1 Transfer function

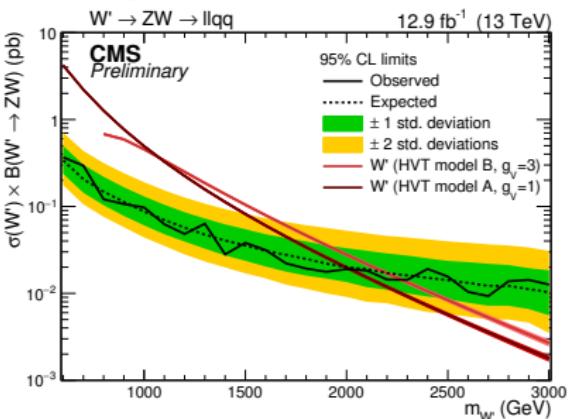
$$\alpha(m_X) = \frac{N_{SR}^{MC}(m_X)}{N_{SB}^{MC}(m_X)}$$

- 2 Fit data  $N_{SB}^{data}(m_X)$  in sidebands
- 3 Background expectation in SR:

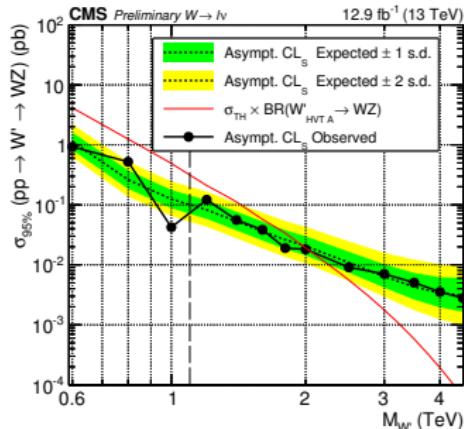
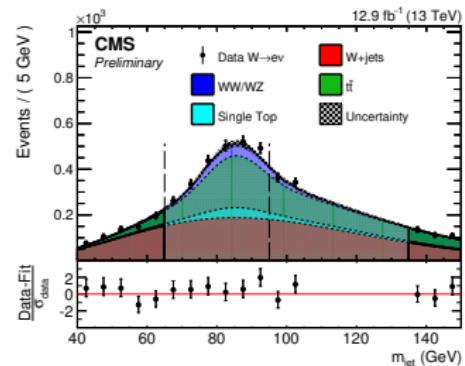
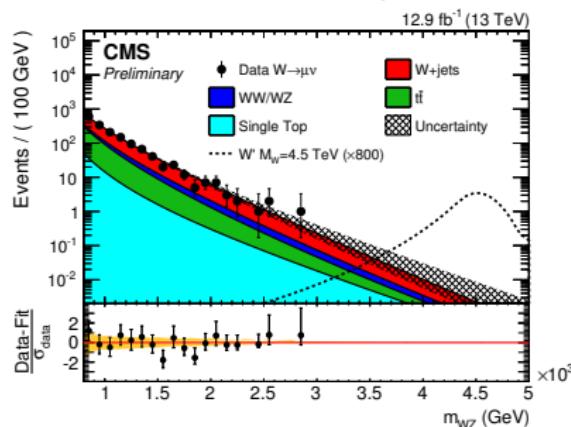
$$N_{SR}^{exp}(m_X) = N_{SB}^{data}(m_X) \times \alpha(m_X)$$



- Data compatible with the SM-only hypothesis
- Exclusion limits at 95% CL of the spin-1  $W'$  singlet
  - HVT model A:  $m_{W'} \lesssim 2.0 \text{ TeV}$
  - HVT model B:  $m_{W'} \gtrsim 2.3 \text{ TeV}$
- Significant improvement w.r.t. 2015 search



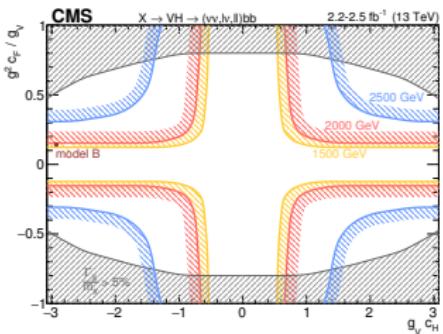
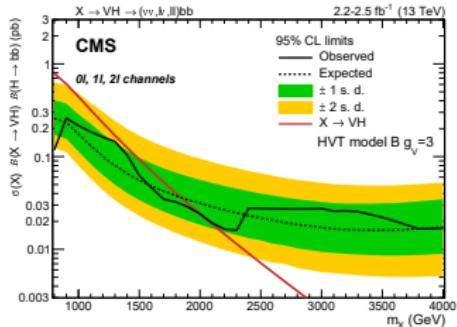
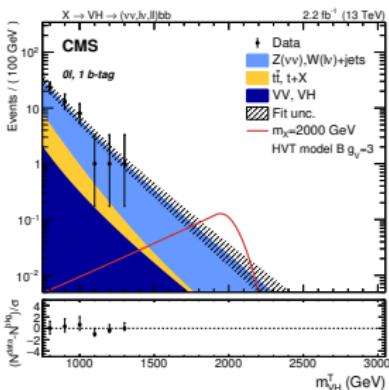
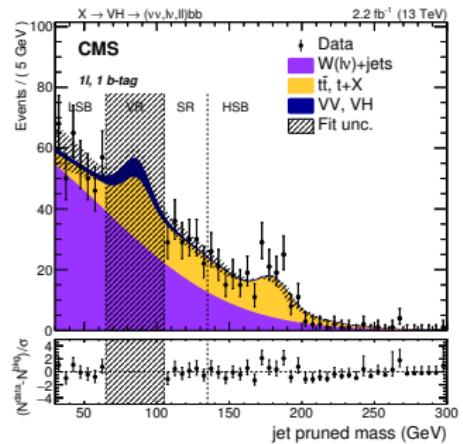
- Search for a resonance decaying to  $WV$  in the leptonic channel ( $W \rightarrow \ell\nu$ ,  $V \rightarrow q\bar{q}$ )
- ICHEP dataset ( $12.9 \text{ fb}^{-1}$ )
- Categorization in  $\tau_{21}$  and  $W/Z$  mass
- Low mass extension down to 600 GeV
- Kinematic reconstruction of  $p_z^\nu$  from  $m_W$
- $\alpha$ -method for background prediction
- Sensitivity similar to  $ZV \rightarrow \ell\ell q\bar{q}$ : HVT model A  $W'$  excluded up to 2.0 TeV



# $X \rightarrow VH$ semileptonic

Phys. Lett. B 765 (2016) 32

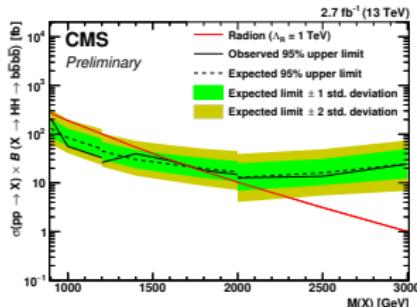
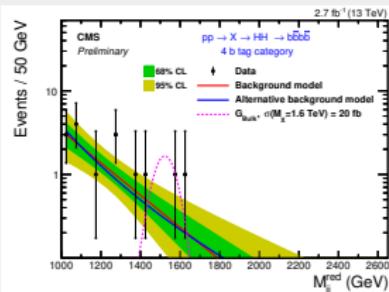
- Search for a resonance decaying to VH in leptonic channels, with 2015 data ( $2.2\text{fb}^{-1}$ )
  - $Z \rightarrow \nu\nu$ : use transverse mass  $m_{VH}^T$
  - $W \rightarrow \ell\nu$ : dedicated top control regions
  - $Z \rightarrow \ell\ell$ : high-efficiency dilepton identification
- b-tagging of the Higgs sub-jets (1 or 2 b-tag)
- $\alpha$ -method for background prediction
- Combined HVT exclusion up to 2.0 TeV in model B



- Search for resonant di-Higgs in all-harmonic (4b) final states
- Two independent background prediction/Higgs tagging methods:

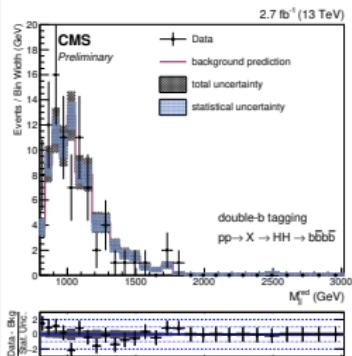
## Smooth fit method

- b-tagging of the sub-jets (3 or 4)
- Fit exponential background



## Alphabet method

- Double-b tagger for  $H \rightarrow b\bar{b}$  identification
- Normalization from mass sidebands
- Shape from “anti-tagged”  $H \rightarrow b\bar{b}$  events

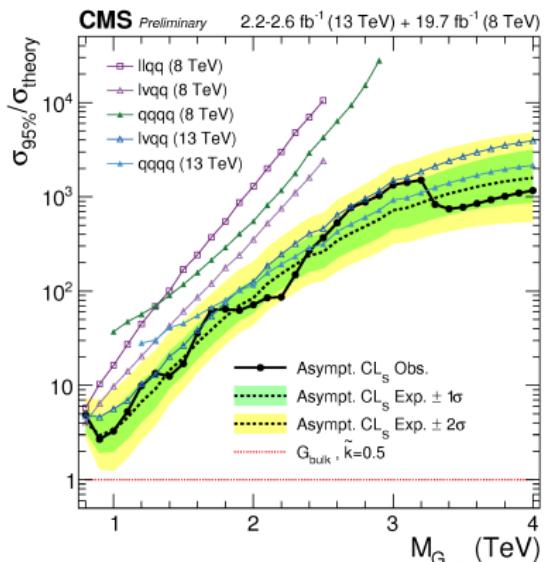
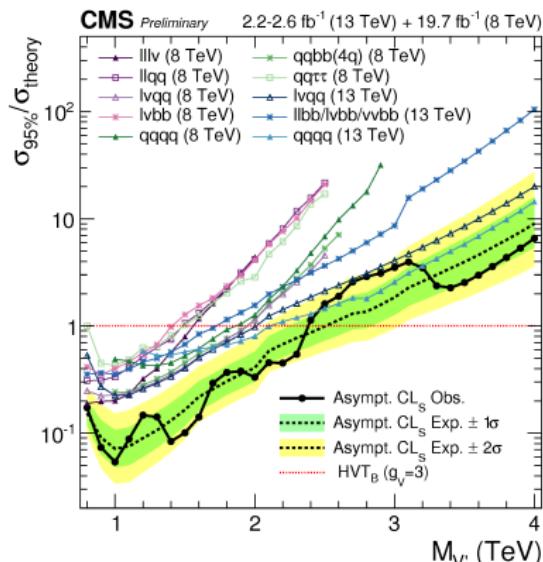


- “Alphabet” used between 0.9-1.2 TeV and 2.0-3.0 TeV
- “Smooth fit” between 1.2-2.0 TeV
- Limit on Radion and Bulk Graviton models

# Combination of the diboson searches

CMS-PAS-B2G-16-007

- Combination between 2015  $\sqrt{s} = 13$  TeV and 2012  $\sqrt{s} = 8$  TeV searches
- Favored by orthogonality between analyses, and common techniques
- Stringent limits on HVT model B:  $m_{V'} < 2.4$  TeV
- Not sensitive enough to exclude Bulk Graviton
- 2016 searches already more sensitive than combination



## 2016 summary

- Two brand-new diboson results for Moriond (VV and VH all-hadronic)
- All major analyses with 2016 data already in an advanced state
- Significant development in boosted object techniques
  - moving from pruning to **soft drop + PUPPI** in 2016
  - prepared to the challenges of 2017 data taking

## Future outlook

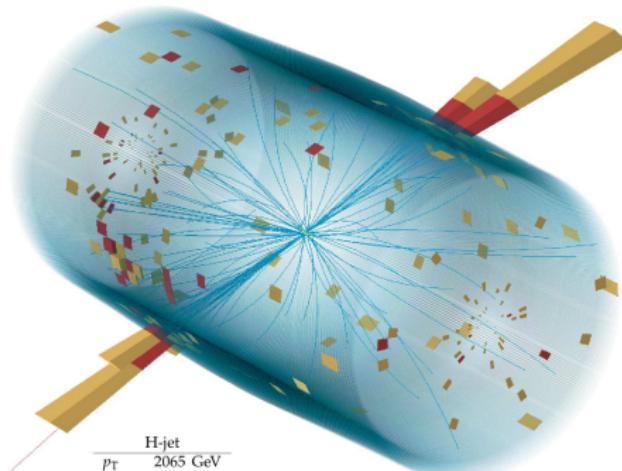
- We had a huge jump in luminosity in 2016
- Immediate effect: the sensitivity of the single analyses already ruled out Run I + 2015 combination
- Situation is going to change in the next future: such a rapid increase won't happen again at LHC
- Exploit excellent synergy between analyses in view of a **combination**:
  - common algorithms for object reconstruction and identification
  - background prediction methods
- Refine analysis and reconstruction techniques, or have **new good ideas!**

# Thank you for your attention!



*W mass, low purity, tight b tag*

Dijet invariant mass  
 $m_{VH} = 4919 \text{ GeV}$



H-jet	
$p_T$	2065 GeV
$\eta$	0.63
$\phi$	0.84
$m_j$	123.7 GeV
b tag	0.95

V-jet
$p_T$ 1962 GeV
$\eta$ -0.65
$\phi$ -2.30
$m_j$ 72.8 GeV
$\tau_{21}$ 0.49

CMS Experiment at LHC, CERN  
 Data recorded: Fri Aug 5 02:45:13 2016 CEST  
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 Lumi section: 287